

The \mathcal{F} -Landscape: Dynamically Determining the Multiverse

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We evolve our *Multiverse Blueprints* to characterize our local neighborhood of the String Landscape and the Multiverse of plausible string, M- and F-theory vacua. Building upon the tripodal foundations of i) the Flipped $SU(5)$ Grand Unified Theory (GUT), ii) extra TeV-Scale vector-like multiplets derived out of F-theory, and iii) the dynamics of No-Scale Supergravity, together dubbed No-Scale \mathcal{F} - $SU(5)$, we demonstrate the existence of a continuous family of solutions which might adeptly describe the dynamics of distinctive universes. This Multiverse landscape of \mathcal{F} - $SU(5)$ solutions, which we shall refer to as the \mathcal{F} -Landscape, accommodates a subset of universes compatible with the presently known experimental uncertainties of our own universe. We show that by secondarily minimizing the minimum of the scalar Higgs potential of each solution within the \mathcal{F} -Landscape, a continuous hypervolume of distinct *minimum minimorum* can be engineered which comprise a regional dominion of universes, with our own universe cast as the bellwether. We conjecture that an experimental signal at the LHC of the No-Scale \mathcal{F} - $SU(5)$ framework's applicability to our own universe might sensibly be extrapolated as corroborating evidence for the role of string, M- and F-theory as a master theory of the Multiverse, with No-Scale supergravity as a crucial and pervasive reinforcing structure.

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I. INTRODUCTION

Contemporary times have witnessed a revolution in string phenomenology, the culmination of decades of enterprise toward the comprehension of a fundamental high energy theory capable of describing the evolution of our observable universe. An unwavering theme that has emerged from this century of innovation is nature's persistent rejection of an intransigent conception of the macrocosm, of which we are just a simple element. Nature's truths have been revealed in pieces and in paradoxes, and have stymied every effort to claim mastery over her mysteries. Whether it be relativistic space and time, quantum entanglement, or black hole event horizons, we have become acclimated to radical revisions in our sense of reality, recognizing that the course of time may force all to acquiesce to axioms initially seeming exotic and fantastic, if they be first synthesized upon rigorous physical maxims.

Progress in the understanding of consistent, meta-stable vacua of string, M- or (predominantly) F-theory flux compactifications has inspired dramatic challenges to the perspective of our prominence in the cosmos. Case in point, it has been postulated that a vast landscape of an astonishing 10^{500} [1, 2] vacua can manifest plausible phenomenology in general. This suggestion implores inquiry as to why our peculiar vacuum transpired out of the landscape. One prevalent philosophy contends that any physically existent universe, whether latent or mature, should correspond to an extremization of probability density in

the primordial quantum froth. Known as the *Anthropic Principle*, this idea implies that our universe, due to its natural existence and presumed singularity, occupies a statistical zenith. Consequently though, this doctrine becomes incurably burdened with fine-tuning complications of the physical properties of our universe. Motivated by the string landscape and other cosmological scenarios, the speculation of a Multiverse germinated as a strategy for overcoming those obstacles endemic to fine-tuning.

In our contemporary *Multiverse Blueprints* [3] we advanced an alternate perspective of our cosmological origins. We suggested that a mere non-zero probability for a universe featuring our measured physical parameters is the necessary and sufficient condition. An observer may inhabit a universe bearing simply a probability of existence which is greater than zero, and not inevitably that which is most probable. Moreover, we argued for the significance of No-Scale Supergravity as a universal foundation allowing for the spontaneous quantum emergence of a cosmologically flat universe. Experimental validation of a No-Scale \mathcal{F} - $SU(5)$ structure for our own universe at the LHC could thus reinforce the role of string, M- and F-theory as a master theory of the Multiverse, with No-Scale supergravity providing an essential model building infrastructure.

We now undertake a first task of engineering in association with our Blueprints [3], considering the possibility of Multiverse model building, or *universe building*. We employ a precision numerical analysis to derive and subsequently classify the features of the No-Scale \mathcal{F} - $SU(5)$

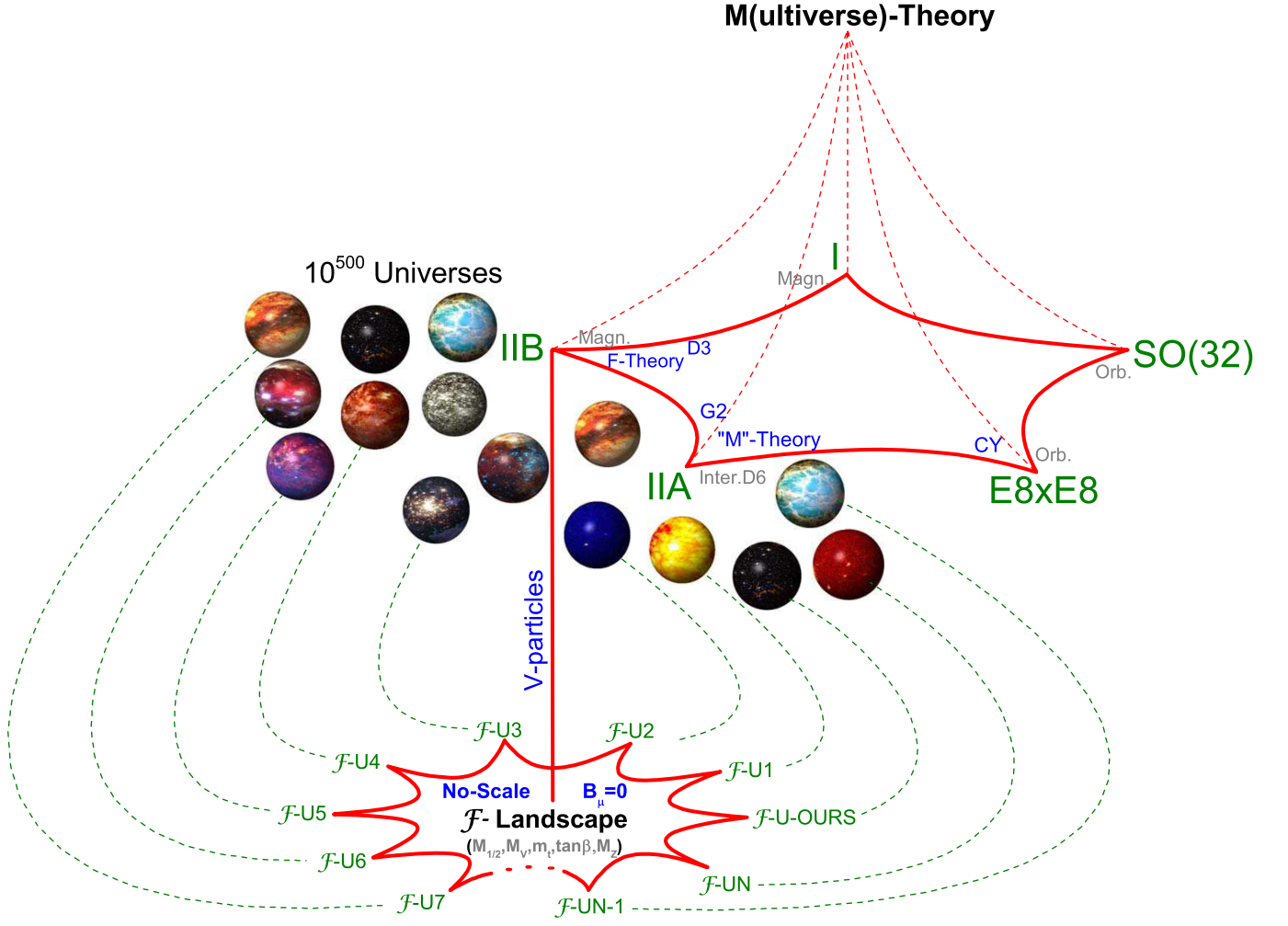


FIG. 1: Contemporary perspective on the String Landscape and M-Theory, where we build the M(ultiverse)-Theory with the \mathcal{F} -Landscape derived out of the tripodal foundation in Fig. 2.

Multiverse, within some local neighborhood of our own universe's phenomenology. By secondarily minimizing each model's scalar Higgs potential minima, under application of the dynamic Super No-Scale condition [3–5], only legitimate electroweak symmetry breaking (EWSB) vacua are viable elements of the solution space. The dynamically selected EWSB vacuum at this point of secondary minimization, which is in correspondence with the stabilization of a string-theoretic modulus, will be identified as the *minimum minimorum* (MM). Thereupon, *all* MM realize our minimal specifications for a greater than zero probability of emerging from the landscape. Hence, we conclude that a contiguous hyperspace of MM in No-Scale \mathcal{F} - $SU(5)$ may fulfill the intended goal of constructing the set of locally adjacent Multiverse constituents, endogenous to the plausible solution set of M- and F-Theory flux compactifications. We stress that application of the dynamic MM vacuum selection criterion elevates the conceptual Multiverse design presented here above a mere scan of the parameter space. We suggest that the resulting construction might rather be regarded

to represent a local dominion of independent universes.

Our paper is organized as follows. First, we shall discuss No-Scale \mathcal{F} - $SU(5)$ in M- and F-Theory flux compactifications, presenting our \mathcal{F} - $SU(5)$ M(ultiverse)-Theory. Next, we engage in a brief review of \mathcal{F} - $SU(5)$, the Super No-Scale condition, and our secondary minimization procedure. In the latter half of our work, we shall demonstrate the minimization of discrete elements within the model space, and extrapolate the results to construct a hyperspace of MM, interpreting the solution space in terms of our local community of universes within the Multiverse.

II. THE \mathcal{F} - $SU(5)$ M(ULTIVERSE)-THEORY

The Standard Model has been confirmed as a correct effective field theory valid up to about 100 GeV. Nonetheless, problems exist, such as the gauge hierarchy problem, charge quantization, and an excessive number of parameters, etc. Moreover, the Standard Model excludes grav-

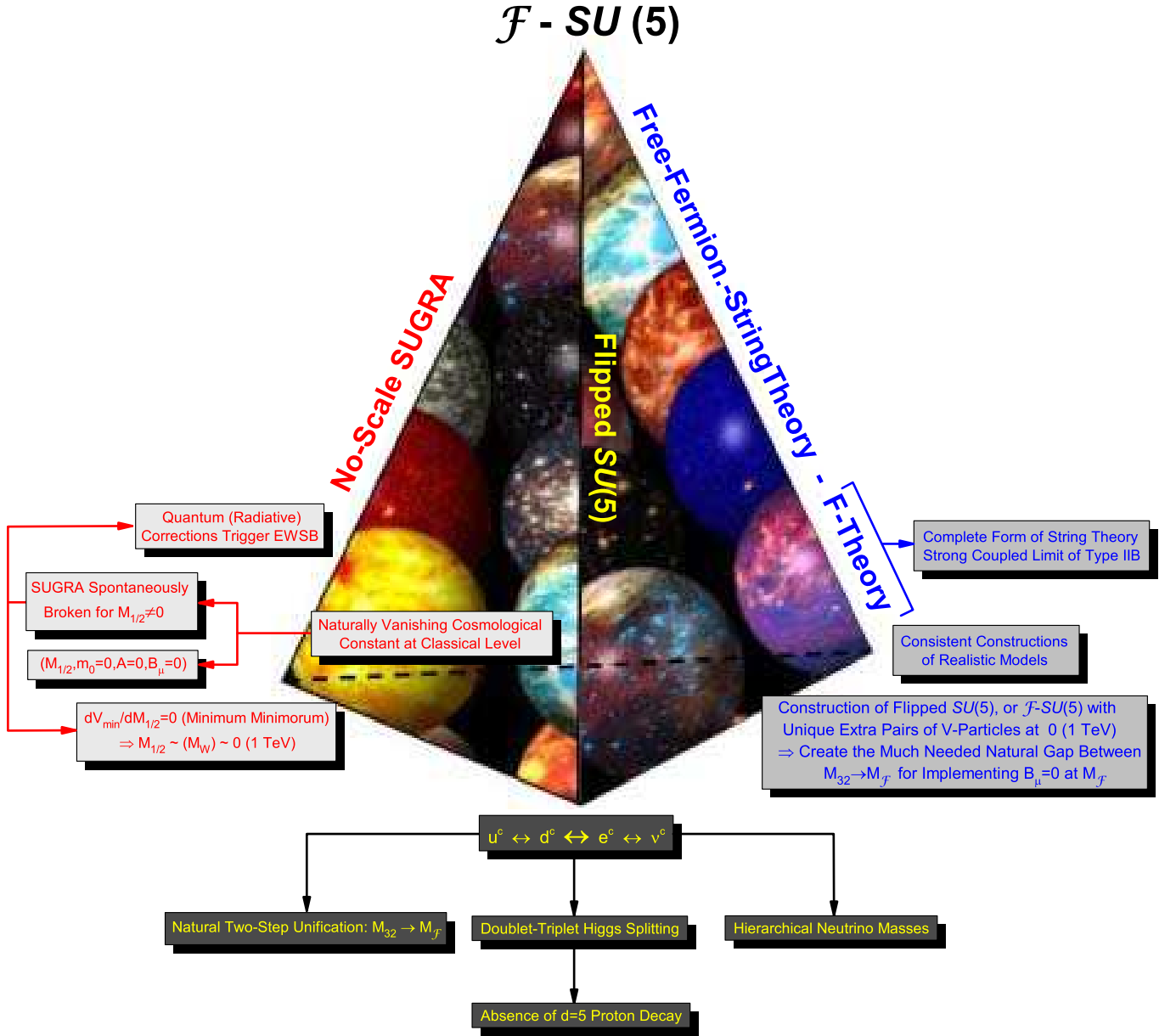


FIG. 2: Tripodal foundation of \mathcal{F} - $SU(5)$, built upon the Flipped $SU(5)$ Grand Unified Theory (GUT), extra TeV-Scale vector-like multiplets derived out of F-theory, and the dynamics of No-Scale Supergravity.

ity. An elegant solution to the gauge hierarchy problem is supersymmetry. In particular, gauge coupling unification can be realized in the supersymmetric SM (SSM), which strongly implies the Grand Unified Theories (GUTs). In the GUTs, not only can we explain the charge quantization, but also reduce the Standard Model parameters due to unification. Therefore, the interesting question is whether there exists a fundamental quantum theory or a final theory that can unify the SSM/GUTS and general relativity?

The most promising candidate for such a theory is superstring theory. Superstring theory is anomaly free only in ten dimensions, hence the extra six space dimensions must be compactified. As portrayed in Fig. 1, there are

five consistent ten-dimensional superstring theories: heterotic $E_8 \times E_8$, heterotic $SO(32)$, Type I $SO(32)$, Type IIA, and Type IIB. Though, this leaves open the question of final unification. Interestingly, Witten pointed out that this distinction is an artifact of perturbation theory, and non-perturbatively these five superstring theories are unified into an eleven-dimensional M-theory [6]. In other words, the five superstring theories are the different perturbative limits of M-theory. Moreover, the twelve-dimensional F-theory can be considered as the strongly coupled formulation of the Type IIB string theory with a varying axion-dilaton field [7], as shown in Fig. 1.

The goal of string phenomenology is to construct the

realistic string vacua, where the SSM/GUTs can be realized and the moduli fields can be stabilized. Such constructions will give us a bridge between the string theory and the low energy realistic particle physics, such that we may test the string models at the Large Hadron Collider (LHC). Initially, string phenomenology was studied mainly in the weakly coupled heterotic string theory. On the other hand, we illustrate in Fig. 1 that in addition to its perturbative heterotic string theory corner, M-Theory unification possesses the other corners such as perturbative Type I, Type IIA and Type IIB superstring theory, which should provide new potentially phenomenologically interesting four-dimensional string models, related to the heterotic models via a web of string dualities. Most notably, with the advent of D-branes [8], we can construct the phenomenologically interesting string models in Type I, Type IIA and Type IIB string theories. Recall that there are five kinds of string models which have been studied extensively: (1) Heterotic $E_8 \times E_8$ string model building. The supersymmetric SM and GUTs can be constructed via the orbifold compactifications [9–11] and the Calabi-Yau manifold compactifications [12, 13]; (2) Free fermionic string model building. Realistic models with clean particle spectra can only be constructed at the Kac-Moody level one [14–20]. Note that the Higgs fields in the adjoint representation or higher can not be generated at the Kac-Moody level one, so only three kinds of models can be constructed: the Standard-like models, Pati-Salam models, and flipped $SU(5)$ models [14–20]. (3) D-brane model building from Type I, Type IIA, and Type IIB theories. There are two major kinds of such models: (i) Intersecting D-brane models or magnetized D-brane models [21–32]; (ii) Orientifolds of Gepner models [33, 34]. (4) M-theory on G_2 manifolds [35, 36]. Those models can be dual to the heterotic models on Calabi-Yau threefolds or to some Type II orientifold models. (5) F-theory GUTs [37–42]. The $SU(5)$ gauge symmetry can be broken down to the SM gauge symmetries by turning on the $U(1)_Y$ fluxes, and the $SO(10)$ gauge symmetry can be broken down to the flipped $SU(5) \times U(1)_X$ gauge symmetries and the $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge symmetries by turning on the $U(1)_X$ and $U(1)_{B-L}$ fluxes respectively.

To stabilize the moduli fields, the string theories with flux compactifications have also been studied [43–48], in which there intriguingly exist huge meta-stable flux vacua. For example, in the Type IIB theory with RR and NSNS flux compactifications, the number of the meta-stable flux vacua can be of order 10^{500} [1, 2]. With a weak anthropic principle, this may provide a solution to the cosmological constant problem and could explain the gauge hierarchy problem as well.

For our work here in this paper, we study only the flipped $SU(5) \times U(1)_X$ models, and we now shall provide a brief review of the minimal flipped $SU(5) \times U(1)_X$ model [49–51]. The gauge group of the flipped $SU(5)$ model is $SU(5) \times U(1)_X$, which can be embedded into

$SO(10)$. We define the generator $U(1)_{Y'}$ in $SU(5)$ as

$$T_{U(1)_{Y'}} = \text{diag} \left(-\frac{1}{3}, -\frac{1}{3}, -\frac{1}{3}, \frac{1}{2}, \frac{1}{2} \right). \quad (1)$$

The hypercharge is given by

$$Q_Y = \frac{1}{5} (Q_X - Q_{Y'}). \quad (2)$$

In addition, there are three families of SM fermions whose quantum numbers under the $SU(5) \times U(1)_X$ gauge group are

$$F_i = (\mathbf{10}, 1), \quad \bar{f}_i = (\bar{\mathbf{5}}, -3), \quad \bar{l}_i = (\mathbf{1}, 5), \quad (3)$$

where $i = 1, 2, 3$.

To break the GUT and electroweak gauge symmetries, we introduce two pairs of Higgs fields

$$\begin{aligned} H &= (\mathbf{10}, 1), \quad \bar{H} = (\bar{\mathbf{10}}, -1), \\ h &= (\mathbf{5}, -2), \quad \bar{h} = (\bar{\mathbf{5}}, 2). \end{aligned} \quad (4)$$

Interestingly, we can naturally solve the doublet-triplet splitting problem via the missing partner mechanism [51], and then the dimension five proton decay from the colored Higgsino exchange can be highly suppressed [51]. The flipped $SU(5) \times U(1)_X$ models have been constructed systematically in the free fermionic string constructions at Kac-Moody level one previously [14–16, 19, 51], and in the F-theory model building recently [37–42], and we represent the flipped $SU(5) \times U(1)_X$ models as one pillar of the foundation for \mathcal{F} - $SU(5)$ in Fig. 2. In the flipped $SU(5) \times U(1)_X$ models, there are two unification scales: the $SU(3)_C \times SU(2)_L$ unification scale M_{32} and the $SU(5) \times U(1)_X$ unification scale $M_{\mathcal{F}}$. To separate the M_{32} and $M_{\mathcal{F}}$ scales and obtain true string-scale gauge coupling unification in free fermionic string models [19, 52] or the decoupling scenario in F-theory models [41, 42], we introduce vector-like particles which form complete flipped $SU(5) \times U(1)_X$ multiplets, and we insert the vector particles and F-Theory as a second pillar in Fig. 2, and also integrate their presence into Fig. 1. In order to avoid the Landau pole problem for the strong coupling constant, we can only introduce the following two sets of vector-like particles around the TeV scale [52]

$$Z1 : XF = (\mathbf{10}, 1), \quad \bar{X}\bar{F} = (\bar{\mathbf{10}}, -1); \quad (5)$$

$$Z2 : XF, \bar{X}\bar{F}, Xl = (\mathbf{1}, -5), \quad \bar{X}\bar{l} = (\mathbf{1}, 5), \quad (6)$$

where

$$XF \equiv (XQ, XD^c, XN^c), \quad \bar{X}\bar{l}_{(\mathbf{1}, 5)} \equiv XE^c. \quad (7)$$

In the prior, XQ, XD^c, XE^c, XN^c have the same quantum numbers as the quark doublet, the right-handed down-type quark, charged lepton, and neutrino, respectively. Such kind of the models have been constructed systematically in the F-theory model building locally and dubbed \mathcal{F} - $SU(5)$ within that context [41, 42]. In this paper, we only consider the flipped $SU(5) \times U(1)_X$ models with Z2 set of vector-like particles. The discussions for the models with Z1 set and heavy threshold corrections [41, 42] are similar.

III. SUPER NO-SCALE SUPERGRAVITY

We now turn to the third and final pillar of the \mathcal{F} - $SU(5)$ foundation in Fig. 2, that of No-Scale supergravity. In the traditional framework, supersymmetry is broken in the hidden sector, and then its breaking effects are mediated to the observable sector via gravity or gauge interactions. In GUTs with gravity mediated supersymmetry breaking, also known as the minimal supergravity (mSUGRA) model, the supersymmetry breaking soft terms can be parameterized by four universal parameters: the gaugino mass $M_{1/2}$, scalar mass M_0 , trilinear soft term A , and the ratio of Higgs VEVs $\tan\beta$ at low energy, plus the sign of the Higgs bilinear mass term μ . The μ term and its bilinear soft term B_μ are determined by the Z -boson mass M_Z and $\tan\beta$ after the electroweak (EW) symmetry breaking.

To solve the cosmological constant problem, No-Scale supergravity was proposed [53–57]. No-scale supergravity is defined as the subset of supergravity models which satisfy the following three constraints [53–57]: (i) The vacuum energy vanishes automatically due to the suitable Kähler potential; (ii) At the minimum of the scalar potential, there are flat directions which leave the gravitino mass $M_{3/2}$ undetermined; (iii) The super-trace quantity $\text{Str}M^2$ is zero at the minimum. Without this, the large one-loop corrections would force $M_{3/2}$ to be either zero or of Planck scale. A simple Kähler potential which satisfies the first two conditions is

$$K = -3\ln(T + \bar{T} - \sum_i \bar{\Phi}_i \Phi_i), \quad (8)$$

where T is a modulus field and Φ_i are matter fields. The third condition is model dependent and can always be satisfied in principle [58]. We emphasize that No-Scale supergravity can be realized in the compactification of the weakly coupled heterotic string theory [59] and the compactification of M-theory on S^1/Z_2 at the leading order [60].

The scalar fields in the above Kähler potential parameterize the coset space $SU(N_C+1, 1)/(SU(N_C+1) \times U(1))$, where N_C is the number of matter fields. Analogous structures appear in the $N \geq 5$ extended supergravity theories [61], for example, $N_C = 4$ for $N = 5$, which can be realized in the compactifications of string theory [59, 60]. The non-compact structure of the symmetry implies that the potential is not only constant but actually identical to zero. In fact, one can easily check that the scalar potential is automatically positive semi-definite, and has a flat direction along the T field. It is interesting that for the simple Kähler potential in Equation (8), we obtain the simplest No-Scale boundary condition $M_0 = A = B_\mu = 0$, while $M_{1/2}$ may be non-zero at the unification scale, allowing for low energy SUSY breaking.

The single relevant modulus field in the simplest string No-Scale supergravity is the Kähler modulus T , a characteristic of the Calabi-Yau manifold, the dilaton coupling

being irrelevant. The F-term of T generates the gravitino mass $M_{3/2}$, which is proportionally equivalent to $M_{1/2}$. Exploiting the simplest No-Scale boundary condition at $M_{\mathcal{F}}$ and running from high energy to low energy under the RGEs, there can be a secondary minimization, or MM, of the minimum of the Higgs potential V_{\min} for the EWSB vacuum. Since V_{\min} depends on $M_{1/2}$, the gaugino mass $M_{1/2}$ is consequently dynamically determined by the equation $dV_{\min}/dM_{1/2} = 0$, aptly referred to as the Super No-Scale mechanism [3–5]. In this paper, we shall define the universe as the MM of the effective Higgs potential for a given set of input parameters.

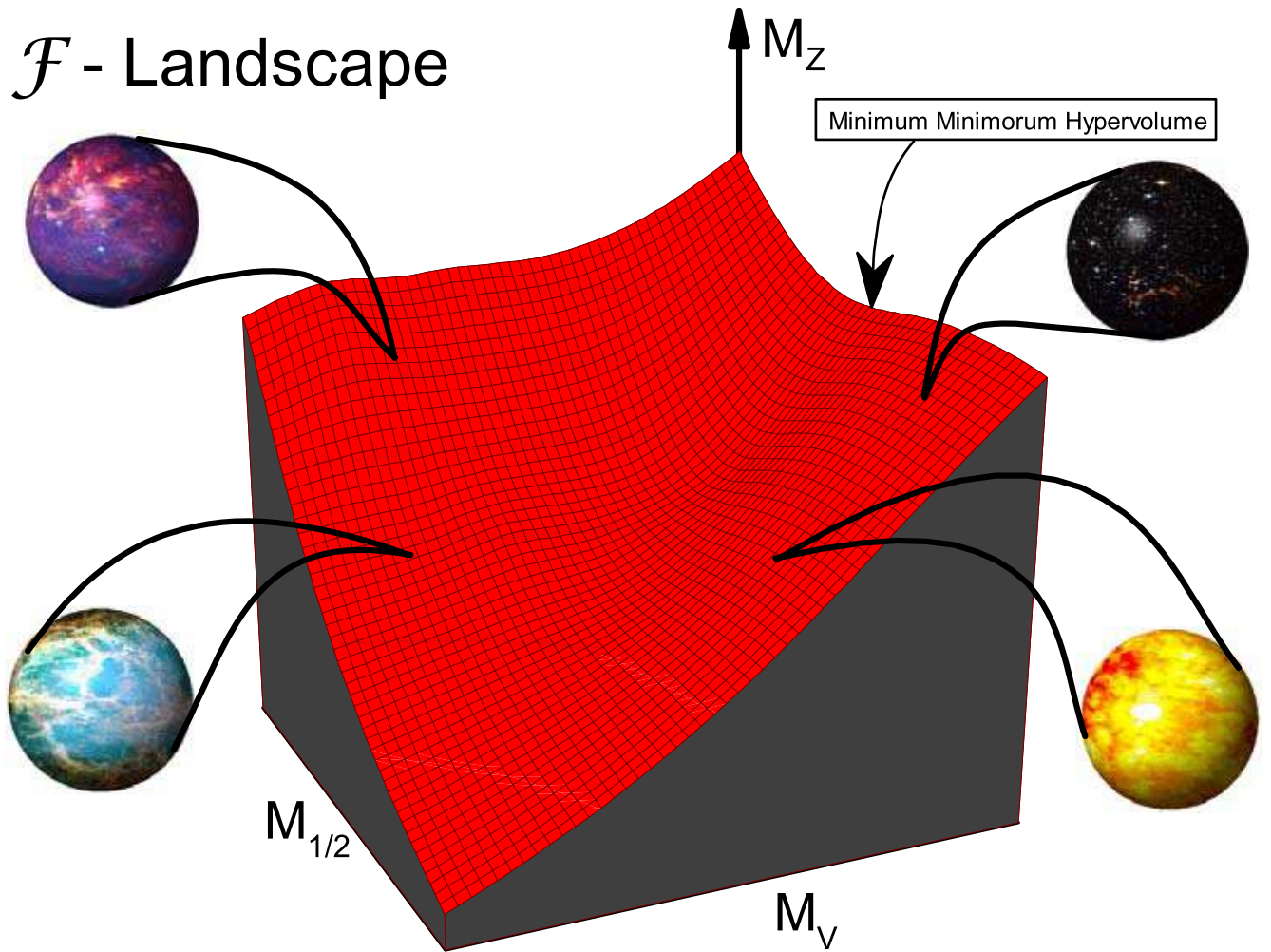
IV. SUPER NO-SCALE \mathcal{F} - $SU(5)$

The model investigated here, dubbed No-Scale \mathcal{F} - $SU(5)$ [3–5, 62–70], unifies the \mathcal{F} -lipped $SU(5)$ Grand Unified Theory (GUT) [49–51] with two pairs of hypothetical TeV-scale vector-like supersymmetric multiplets with origins in \mathcal{F} -theory [41, 42, 52, 71, 72] and the dynamically established boundary conditions of No-Scale supergravity [53–57], as exhibited in Fig. 2. A more complete review of this model is available in the appendix of Ref. [65].

We have previously defined an exceptionally constrained Golden Point [62] and Golden Strip [63, 70] using the dynamically established boundary conditions of No-Scale supergravity at the \mathcal{F} - $SU(5)$ unification scale that satisfied all the latest experimental constraints while also generating an imminently observable proton decay rate [73]. The most limiting constraint imposed upon the viable parameter space is the unification scale boundary on $B_\mu = 0$. Moreover, the $M_{1/2}$ boundary gaugino mass and the ratio of the Higgs vacuum expectation values (VEVs) $\tan\beta$ were dynamically determined by applying the Super No-Scale condition for the dynamic stabilization of the stringy modulus related to $M_{1/2}$ [3–5].

The total set of supersymmetry breaking soft terms evolve from the single parameter $M_{1/2}$ in the simplest No-Scale supergravity, and as a result, the particle spectra are proportionally comparable up to an overall rescaling on $M_{1/2}$, leaving the majority of the “internal” physical properties invariant. This rescaling capability on $M_{1/2}$ is atypical and has generally not been observed in dissimilar supersymmetry models, due to the presence of a large parameterization freedom, particularly with respect to a second independent boundary mass M_0 for scalar fields. The dependence on the vector-like mass parameter is rather weak, though this rescaling symmetry can be broken to a small degree by M_V .

If we temporarily fix the top quark mass m_t and vector-like mass M_V , the dual EWSB minimization conditions first ascertain the Higgs bilinear mass term μ at $M_{\mathcal{F}}$, and secondly, since $B_\mu(M_{\mathcal{F}}) = 0$ has been previously fixed by the No-Scale boundary conditions, establishes $\tan\beta$ as an implicit function of the universal gaugino boundary mass $M_{1/2}$. The minimum of the electroweak Higgs potential



Each point in the \mathcal{F} -Landscape is a distinctive \mathcal{F} -Universe

FIG. 3: Heuristic depiction of the \mathcal{F} -Landscape in terms of the parameters $M_{1/2}$, M_V , and M_Z , with four indiscriminate universes shown at random points on the landscape. The hypervolume illustrated is a contiguous region of minimum minimorum, each minimum minimorum representing the minimum of the 1-loop scalar Higgs potential and an EWSB vacuum.

$(V_{EW})_{min}$ depends on $M_{1/2}$, and furthermore, the gaugino mass $M_{1/2}$ is related to the F-term of the modulus in string models, hence the gaugino mass is determined by the equation $d(V_{EW})_{min}/dM_{1/2} = 0$ due to the modulus stabilization [54, 57]. At this locally smallest value of $V_{min}(M_{1/2})$, which is the MM, the dynamic determination of $M_{1/2}$ is realized, and this is the Super No-Scale supergravity condition.

In this work we apply the expanded procedure implemented in [3, 5], where the chief difference is that we now permit a fluctuation not just of $M_{1/2}$, which is related to the F-term of the Kähler modulus T in the weakly coupled heterotic $E_8 \times E_8$ string theory or in M-theory on S^1/Z_2 , but of the GUT scale Higgs modulus as well, as represented in the mass scale M_{32} at which the $SU(3) \times SU(2)_L$ couplings first unify. Using the low energy couplings as input, we could presume M_{32} to be a “given” quantity. In fact, beginning from the measured

Standard Model gauge couplings and fermion Yukawa couplings at the LEP 91.187 GeV electroweak scale, we can compute both M_{32} and the final unification scale $M_{\mathcal{F}}$, and consequently the unified gauge coupling and Standard Model fermion Yukawa couplings at $M_{\mathcal{F}}$, through running of the RGEs. Nonetheless, since the VEVs of the GUT Higgs fields H and \bar{H} are considered here as free parameters, the GUT scale M_{32} cannot be held constant either. As a result, the low energy Standard Model gauge couplings, specifically the $SU(2)_L$ gauge coupling g_2 , will also run freely via this feedback from M_{32} . Upon realization of the existence of a second dynamic modulus, we do secure μ to a constant value, which being a basic numerical parameter, should be managed similarly to the top quark and vector-like mass parameters, and as such, a constant μ slice of the V_{min} hyper-surface is exacted out possessing a minimum value of the effective Higgs potential at the minimum of the parabolic curve. By removing

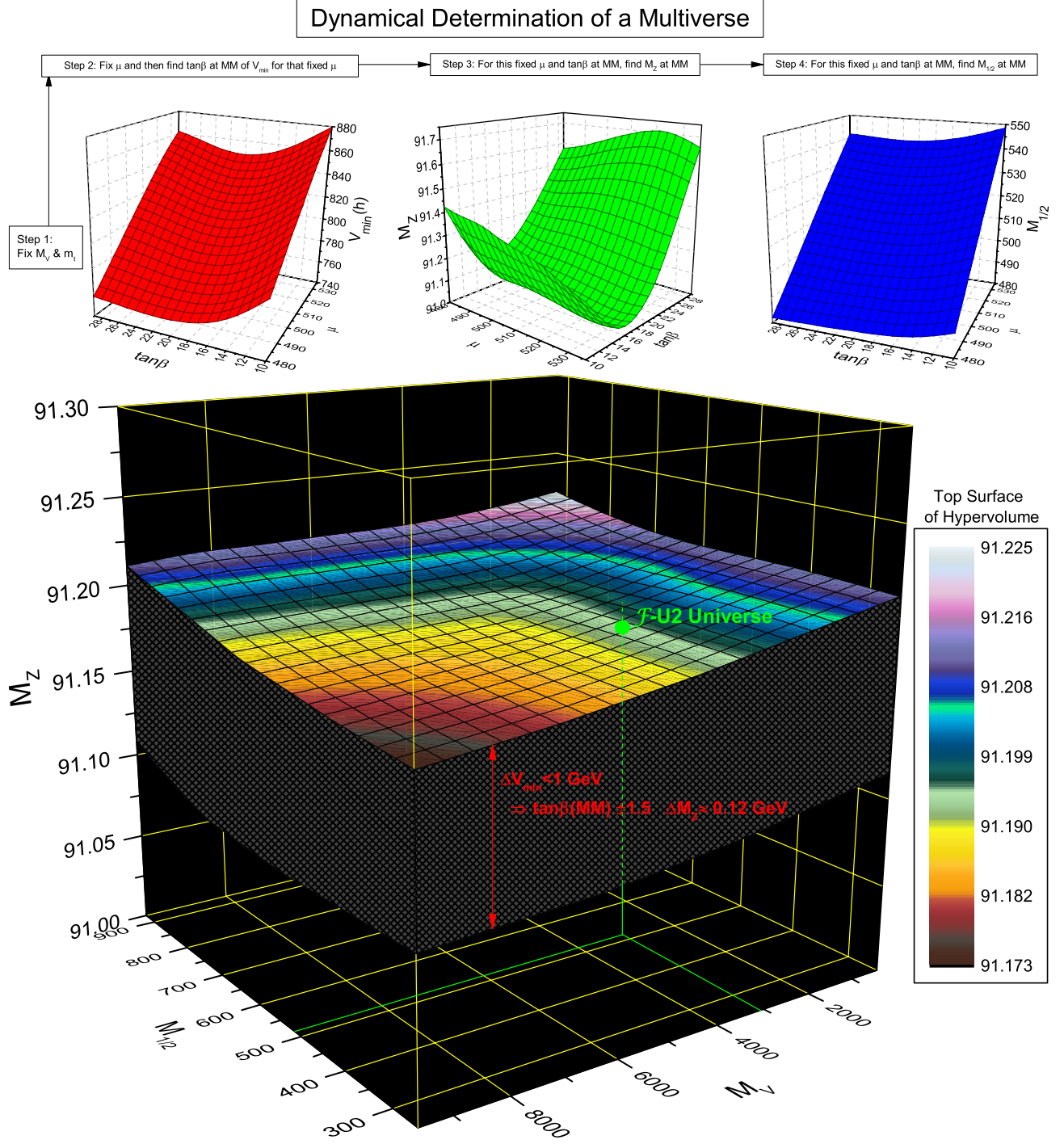


FIG. 4: Logical flow depicting the process of dynamically determining a Multiverse. The upper three plot spaces show the $B_\mu=0$ hypersurfaces for a fixed set of (M_V, m_t) . The lower plot space is generated by dynamically determining numerous points throughout the model space to estimate the hypervolume of minimum minimorum. Here we show the coordinates of universe \mathcal{F} -U2 in the lower plot from Table I, which represents a plausible candidate for our universe. The thickness of the volume is approximated by placing a constraint of $\Delta V_{min}(h) < 1 \text{ GeV}$ at the minimum minimorum, similar in scale to the QCD corrections at the second loop. This results in a deviation of ± 1.5 on the $\tan\beta$ at the minimum minimorum, translating into a 0.12 GeV uncertainty on the dynamically determined value of the electroweak scale M_Z .

the slice of fixed μ from the V_{\min} hyper-surface, the secondary minimization condition on $\tan\beta$ is effectively rotated, albeit quite moderately, relative to the procedure of Ref. ([4]). The minimization we advocate here, referencing $M_{1/2}$, M_{32} and $\tan\beta$, is again dependent upon M_V and m_t , while the determination of $\tan\beta$ in [4], by contrast, left M_V and m_t invariant. We emphasize the mutual consistency of the results, given the realization that an effective minimization requires modulation of all three parameters in order to assert a concurrent dynamical determination of all three parameters. It moreover confronts the difficulties of the SUSY breaking scale and gauge hierarchy [4], insomuch as $M_{1/2}$ is determined dynamically.

Practically speaking, the variation of M_{32} is accomplished in the reverse by a small programmatic variation of the Weinberg angle, with $\sin^2(\theta_W) \simeq 0.236$, in excellent agreement with experiment, maintaining the strong and electromagnetic couplings at their physically measured values. The magnitude of the Higgs VEV is in effect fixed, so the small shifting of the Weinberg Angle is achieved by a minor deviation in the Z -boson mass. Since the vital electroweak Higgs VEV is not a significant ingredient of the variation, we exercise caution when stating our claim for the dynamical determination of $M_Z \simeq 91.187$ GeV. Although, in *conjunction* with the radiative electroweak symmetry breaking [74, 75] numerically implemented within the **SuSpect 2.34** code base [76], the fixing of the Higgs VEV and the determination of the electroweak scale may also plausibly be considered legitimate dynamic output, *if* one posits the M_F scale input to be available *a priori*.

There is a pair of Higgs doublets H_u and H_d which give mass to the up-type quarks and down-type quarks/charged leptons, respectively, in a supersymmetric Standard Model. The one-loop effective Higgs potential in the 't Hooft-Landau gauge and in the $\overline{\text{DR}}$ scheme is given by

$$V_{\text{eff}} = V_0(H_u^0, H_d^0) + V_1(H_u^0, H_d^0), \quad (9)$$

where

$$V_0 = (\mu^2 + m_{H_u}^2)(H_u^0)^2 + (\mu^2 + m_{H_d}^2)(H_d^0)^2 - 2B_\mu \mu H_u^0 H_d^0 + \frac{g_2^2 + g_Y^2}{8} [(H_u^0)^2 - (H_d^0)^2]^2 \quad (10)$$

$$V_1 = \sum_i \frac{n_i}{64\pi^2} m_i^4(\phi) \left(\ln \frac{m_i^2(\phi)}{Q^2} - \frac{3}{2} \right), \quad (11)$$

where $m_{H_u}^2$ and $m_{H_d}^2$ are the supersymmetry breaking soft masses, g_2 and g_Y are respectively the gauge couplings of $SU(2)_L$ and $U(1)_Y$, n_i and $m_i^2(\phi)$ are respectively the degree of freedom and mass for ϕ_i , and Q is the renormalization scale. We have revised the **SuSpect 2.34** code base [76] to incorporate our specialized No-Scale \mathcal{F} - $SU(5)$ with vector-like mass algorithm, and appropriately implement two-loop RGE running for the SM

gauge couplings, and one-loop RGE running for the SM fermion Yukawa couplings, μ term, and SUSY breaking soft terms.

V. THE \mathcal{F} -LANDSCAPE

The methodology of Refs. [3, 5] for computing the MM summarized in the previous section had only been applied to a single point within the viable \mathcal{F} - $SU(5)$ parameter space in our previous work. We now seek to originate a full *landscape* of the local \mathcal{F} - $SU(5)$ model space by calculating the MM for a discrete set of points representative of the neighboring model space that presently subsists in the vicinity of the experimental uncertainties of our own universe. Subsequently, we extrapolate the sampled findings to estimate a hypervolume of solutions for a more comprehensive panorama of the model space. We shall then interpret this landscape in the context of the *Multiverse Blueprints* [3], designating this subdivision as our local Multiverse community. In a broader sense, the Multiverse landscape is, of course, not limited to that zone which lies within our experimental uncertainty, though our purpose here is only initially to seek the prospective structure of an \mathcal{F} - $SU(5)$ local Multiverse, within an acceptable introductory level of precision. Each point within this No-Scale \mathcal{F} - $SU(5)$ Multiverse landscape of solutions, which we shall heretofore refer to as the \mathcal{F} -Landscape, can be interpreted as a distinct universe within our regional dominion of universes, as heuristically illustrated in Fig. 3, where we portray four diverse universe samples active within the \mathcal{F} -Landscape. The final pane of Fig. 1 demonstrates the resulting solution space, with application of rigorous numerics. As elaborated in [3], testing of the No-Scale \mathcal{F} - $SU(5)$ framework at the LHC is in some sense likewise a broader test of the framework of the String Landscape and the Multiverse of plausible string, M- and F-theory vacua. One can boldly speculate that substantiation of a No-Scale \mathcal{F} - $SU(5)$ configuration for our universe at the LHC offers indirect support for a local dominion of \mathcal{F} - $SU(5)$ universes.

A modest sampling of satisfactory \mathcal{F} - $SU(5)$ points are extracted from the experimentally viable parameter space that satisfies the “bare-minimal” constraints of [5], in order to compute the MM in conformity with our conventional methodology summarized in the previous section. The outermost borders of the experimentally viable parameter space presented in [5] are circumscribed from the bare-minimal constraints, though these constraints in principle are applicable only to our universe and not the Multiverse in general. Nevertheless, the model space persisting within this constrained perimeter presents a generous supply of archetype universes to explore and accordingly construct a hypervolume of solutions. To recapitulate, the bare-minimal constraints for our universe are defined by compatibility with the world average top quark mass $m_t = 173.3 \pm 1.1$ GeV [77], the prediction of

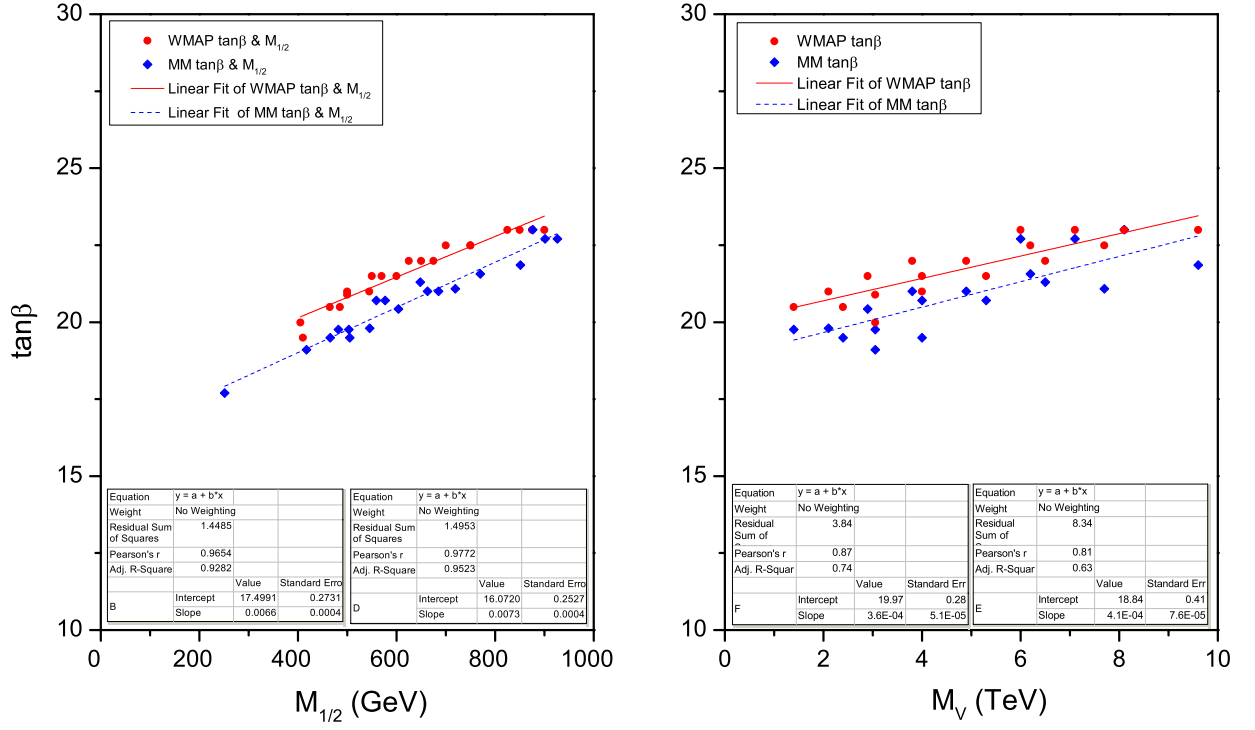


FIG. 5: Scatter diagram comparing the $\tan\beta$ necessary for generating the WMAP-7 relic density (circles) and the $\tan\beta$ at the minimum minimorum (diamonds), for similar values of $M_{1/2}$ and M_V , in GeV. The linear fitted lines are nearly parallel and within the ± 1.5 constraint on $\tan\beta$ at the minimum minimorum, indicating that the experimentally driven bottom-up strategy is self-consistent with the theoretically motivated top-down strategy, hinting at deep fundamental correlations within the model.

a suitable candidate source of cold dark matter (CDM) relic density matching the upper and lower thresholds $0.1088 \leq \Omega_{CDM} \leq 0.1158$ set by the WMAP-7 measurements [78], a rigid prohibition against a charged lightest supersymmetric particle (LSP), compatibility with the precision LEP constraints on the lightest CP-even Higgs boson ($m_h \geq 114$ GeV [79, 80]) and other light SUSY chargino, stau, and neutralino mass content, and a self-consistency specification on the dynamically evolved value of B_μ measured at the boundary scale $M_{\mathcal{F}}$. An uncertainty of ± 1 GeV on $B_\mu = 0$ is allowed, consistent with the induced variation from fluctuation of the strong coupling within its error bounds and the expected scale of radiative electroweak (EW) corrections. The lone constraint above that is necessarily mandatory for the Multiverse is that of the condition on the B-parameter at the $M_{\mathcal{F}}$ scale, since there is certainly no prerequisite for any of these other constrained parameters to inhabit within or even adjacent to the experimentally established uncertainties for our universe, although for our study here we prefer to remain nearby the local experimental ambiguities. The cumulative effect of these bare-minimal constraints distinctively shapes the experimentally viable parameter space germane to our universe into the uniquely formed profile situated in the $(M_{1/2}, M_V)$ plane exhibited in Ref. [5], from a tapered light mass region with a lower bound of $\tan\beta = 19.4$ into a more expansive heav-

ier region that ceases sharply with the charged stau LSP exclusion around $\tan\beta \simeq 23$. Correspondingly, we shall not journey too far afield from this narrow region of $\tan\beta$ or the world average top quark periphery.

The production of the hypervolume of solutions is initiated by mining the bare-minimally constrained wedge region in Ref. [5] for prospective universes from which to compute $V_{min}(h)$, carrying precision equivalent to the LEP constraints on the electroweak scale M_Z . In [3, 5], we executed the minimization procedure for a single specific fixed numerical value of μ only, so in essence, here we are broadening the blueprint of [3, 5] to encompass an extensive range of μ , utilizing our prescribed freedom of the numerical parameter. The secondary minimization procedure is thus enlarged by an order of cardinality, such that we may position the numerical value of μ to any figure we require, essentially dynamically determining in principle all $M_{1/2}$, $\tan\beta$, and M_Z for any preset permutation of M_V and m_t . This prescription can be replicated for an indefinite quantity of regional points within the model space in order to extrapolate the outcome to an estimated hypervolume comprising our local dominion of universes. A logically sequenced rendering of the prescription for dynamically determining a Multiverse is illustrated in Fig. 4, with the top half of the Fig. 4 space elucidating the minimization procedure for a unique predetermined duo of M_V and m_t , while the

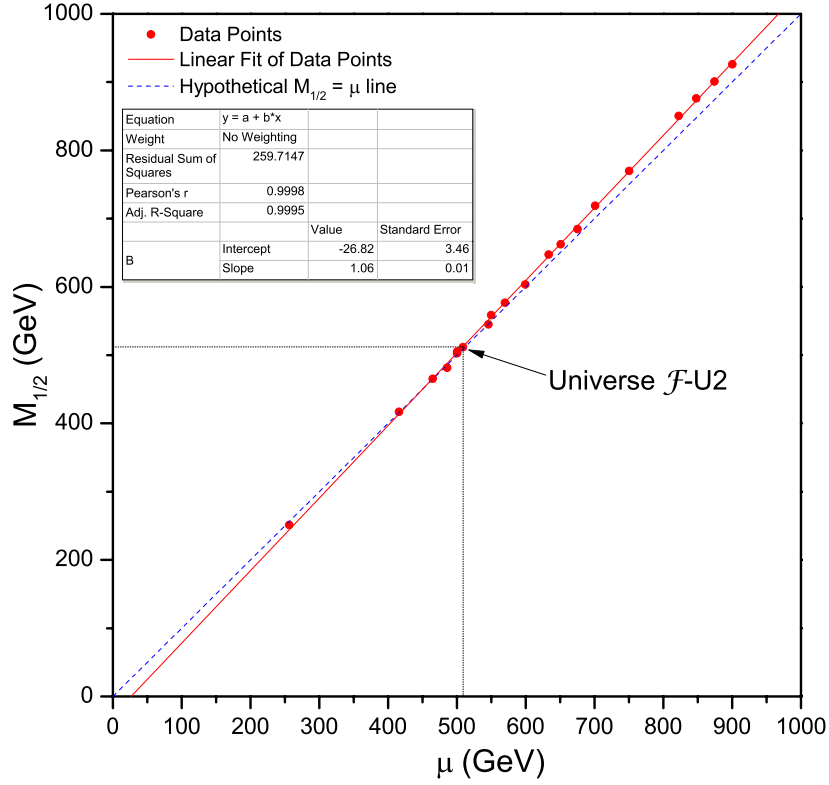


FIG. 6: Data points depicting the linear relationship between $M_{1/2}$ and μ , in GeV. Universe \mathcal{F} -U2, a phenomenologically favored candidate for our universe and also the most adept at explaining the CMS and ATLAS observations at the LHC, is highlighted for its noteworthy position right at the intersection of the data points linear fit and the hypothetical $M_{1/2} = \mu$ line.

bottom half of the plot space reveals a depiction of the conjectural hypervolume of universes.

Explicitly, the flow demonstrated in Fig. 4, after selection of a fixed combination of M_V and m_t , proceeds first to pinpoint $\tan\beta$ at the minimum of the 1-loop Higgs potential $V_{min}(h)$ for a precise numerical value of μ , as depicted in the upper left element, which is now deemed the MM. The curved grid surfaces illustrated in the top half of the Fig. 4 space characterize the hypersurface of $B_\mu = 0$ solutions. The effect of the ± 1 GeV induced electroweak scale variations on the $B_\mu = 0$ condition translates into a small thickness of the $B_\mu = 0$ hypersurfaces in the top half of the Fig. 4 space, though we suppress this in the diagrams here for simplicity. At first glance, $\tan\beta$ at the MM appears to be constant in Fig. 4, though in fact it is not, as $\tan\beta$ at the MM experiences a slight gradual continuous variation as the numerical value of μ is continuously adjusted. Once $\tan\beta$ at the MM for our selection of μ is discovered, we can then resolve the corresponding M_Z and $M_{1/2}$ at this MM by analyzing the center and right plots in the top half of the Fig. 4 space. We have in no way up to this point deviated from the methodology of Refs. [3, 5]. We have only demonstrated that guidelines established in Refs. [3, 5] can be broadened to incorporate the selection of any μ , such that the freedom on the bilinear μ parameter can in some sense be envisioned as a dial that can “tune” $M_{1/2}$, $\tan\beta$, and

M_Z to that of any distinctive universe, for any and all prescribed sets of M_V and m_t , traversing the $B_\mu = 0$ hypersurfaces.

The multistep minimization procedure is copied for a sizable quantity of points in the model space, generating the solution space in the lower half plot of Fig. 4 through an extrapolation of the discrete returns. Only those sub one GeV perturbations about the minimum of the 1-loop Higgs potential are preserved, which we judge to be comparable in scale to the QCD corrections to the Higgs potential at the second loop. This constraint confines the value of $\tan\beta$ at the MM to live within an expected ± 1.5 deviation around the absolute minimum of $V_{min}(h)$. Consequently, we can project the ensuing variation in M_Z to be about ± 0.12 GeV at the MM. Thusly, over and above the freedom in μ to select different universes by “tuning” $M_{1/2}$, $\tan\beta$, and M_Z along a continuous string of MM, we must further recognize the indeterminate nature of these parameters at the MM from the QCD fluctuations providing some discretion on confinement of the MM to this theoretic one-dimensional string. Yet, it is essential to bear in mind that altering any one of these parameters will demand a compensating adjustment in one or more of the remaining parameters in order to transit along the $B_\mu = 0$ direction, engendering an additional unique point in the hypervolume of solutions, i.e. a unique universe in the Multiverse. These

TABLE I: Ten randomly selected benchmark universes, with the exception of universe $\mathcal{F} - U2$, with their model parameters and supersymmetry spectrum, in GeV. Universe $\mathcal{F} - U2$ was selected for its favorable phenomenological characteristics matching those of our universe, this being only one example of a universe that can dynamically determine our electroweak scale M_Z , though with an $M_{1/2}$ capable of generating LHC events in line with the actual data observations of the CMS and ATLAS Collaborations.

$\mathcal{F} - \text{Universe}$	$M_{1/2}$	M_V	m_t	$\tan\beta$	M_Z	μ	B_μ	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}/m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\tau}_1}$	$m_{\tilde{e}_R}$	$m_{\tilde{t}_1}$	$m_{\tilde{b}_R}$	$m_{\tilde{u}_R}$	$m_{\tilde{d}_R}$	$m_{\tilde{g}}$	m_h	m_A
$\mathcal{F} - U1$	482	1400	174.4	19.8	91.152	486	-0.22	91	198	107	183	514	878	990	1029	655	121.1	924
$\mathcal{F} - U2$	512	3050	173.1	21.0	91.187	509	0.39	101	218	110	193	554	906	1016	1054	705	120.0	923
$\mathcal{F} - U3$	512	4000	172.6	19.5	91.118	506	0.14	102	219	127	193	554	901	1003	1040	707	119.4	918
$\mathcal{F} - U4$	546	2100	174.3	19.8	91.145	545	-0.20	106	229	128	206	591	975	1092	1134	741	121.3	1011
$\mathcal{F} - U5$	577	4000	173.2	20.7	91.141	570	-0.75	116	249	134	217	631	1007	1123	1164	791	120.5	1017
$\mathcal{F} - U6$	604	2900	174.0	20.4	91.127	599	0.68	120	257	143	226	663	1062	1186	1229	820	121.5	1083
$\mathcal{F} - U7$	648	6500	172.8	21.3	91.143	633	0.86	134	286	153	242	716	1109	1231	1274	889	120.5	1097
$\mathcal{F} - U8$	719	7700	173.2	21.1	91.126	701	-0.88	151	320	177	268	797	1221	1350	1396	983	121.2	1203
$\mathcal{F} - U9$	877	8100	173.6	23.0	91.165	845	0.31	187	394	199	325	980	1466	1621	1676	1183	122.3	1414
$\mathcal{F} - U10$	901	7100	174.0	22.7	91.143	874	-0.54	192	404	206	334	1006	1512	1673	1730	1211	123.0	1469

small fluctuations about the MM induce the diagrammed thickness of the hypervolume advertised in Fig. 4, where each singular point in the illustrated hypervolume exemplifies an individual universe in the Multiverse.

The points employed in the compilation of the $B_\mu = 0$ hypersurface and hypervolume of Multiverse solutions in Fig. 4 were extracted from the experimentally viable parameter space delineated in Ref. [5], where the contours of $\tan\beta$ defining those regions consistent with the WMAP-7 relic density measurements progressively scale with both $M_{1/2}$ and M_V . As noted earlier, the WMAP-7 experimentally allowed parameter space spans from $\tan\beta = 19.4$ to around $\tan\beta \simeq 23$, enveloping those regions of the model space regarded as credible contenders for our universe from a bottom-up experimental perspective. From a Multiverse frame of reference, the WMAP-7 region is extraneous, as any universe within the \mathcal{F} -Landscape may possess an intrinsic “WMAP” dark matter density, so to speak. In the process of dynamically determining the $M_{1/2}$, $\tan\beta$, and M_Z at the MM, relevant to the top-down theoretical perspective, there is little reason to anticipate (at least not from the point of view of an island universe) that the bottom-up and top-down techniques should be self-consistent at more than just a single point. Nevertheless, this remarkable correspondence is unquestionably what is discovered, prompting curiosity at whether the correlation stems from a deep physical motivation. In particular, the parallel transport of parameterization freedom exhibited by the phenomenological and dynamical treatments appears to support the conjectural application of this framework to a continuum of locally adjacent universes, each individually seated at its own dynamic MM.

A generous selection of points is plotted in Fig. 5, highlighting the $M_{1/2}$, M_V , and $\tan\beta$ that can produce the WMAP-7 relic density, in conjunction with the fixing of $\tan\beta$ at the absolute MM, given by a numerical value of μ which in turn correlates with an $M_{1/2}$ intimately re-

sembling the WMAP-7 $M_{1/2}$. Note that the WMAP M_V is equivalent to the M_V at the MM since the vector mass is not a dynamically determined parameter. As visibly depicted in Fig. 5, the slope of the two linearly fitted lines are practically parallel, only displaced by a small delta on $\tan\beta$, comfortably within our imposed ± 1.5 variance on $\tan\beta$ from QCD 2-loop corrections. To recap, when scrutinizing only the precise MM, the $\tan\beta$ at this exact MM scales nearly perfectly with the WMAP-7 $\tan\beta$, or plainly stated, $\tan\beta(\text{WMAP}) = \tan\beta(\text{MM})$. That this extraordinary self-consistency should connect the experimentally and theoretically inspired strategies is by no means guaranteed, nor do we deem it to be accident. It epitomizes the multitude of profound correlations which have been observed amid our exhaustive exploration of the No-Scale \mathcal{F} - $SU(5)$ models.

A further noteworthy aspect emerging from the constitution of the Multiverse hypervolume is a rather suggestive linkage between the Higgs bilinear mass term μ and the gaugino mass $M_{1/2}$. With $\tan\beta$ constrained to the local vicinity of the 20 value through the phenomenological scheme, we wish to emphasize that this is consistent with the original motivation of No-Scale GUTs, since the Super No-Scale condition itself becomes quite subtle if the vector-like particle mass is much larger than the sparticle masses [53–57]. Interestingly, we find for the \mathcal{F} -Landscape that $M_{1/2}$ is virtually equal to μ across the entire region of the model space investigated here, as sketched in Fig. 6. This may be an effect of the strong No-Scale boundary conditions and might moreover have deep implications to the solution of the μ problem in the supersymmetric standard model [81]. The fact that μ and M_V might be generated from the same mechanism [81] represents an additional naturalness argument for the suggestion that μ and M_V should be of the same order. Likewise as intriguing, Fig. 6 indicates $M_{1/2}$ and μ are definitively equal in an abbreviated segment amidst the most phenomenologically preferred region of $M_{1/2} \sim$

500 GeV.

Ten benchmark universes are enumerated in Table I, introducing \mathcal{F} -U2 as a suitable contender for our universe, with the $(M_{1/2}, M_V, M_Z)$ coordinates indigenous to the hypervolume annotated in Fig. 4. Universe \mathcal{F} -U2 possesses quite desirable phenomenological characteristics, deserving of its emphasis here. In particular, \mathcal{F} -U2 is emblematic of the class of universes endemic to the Golden Strip [70], fulfilling all the most current experimental constraints to embody an exemplary target for supersymmetry discovery at the LHC. Moreover, the gaugino mass $M_{1/2}$ of universe \mathcal{F} -U2 adeptly explains compelling excesses in multijet events thus far observed by the CMS and ATLAS Collaborations at the LHC, producing categorical statistical fittings upon the genuine data event observations, discussed in [81].

Evidently from Fig. 4, distinct universes will nonetheless enjoy complementary facets as evidenced by their equivalent \mathcal{F} - $SU(5)$ model parameters. For instance, to borrow a traditional metaphor for associating companion entities, in Fig. 7 we discern that universes with invariant M_V can be promulgated as *sister universes* in the vector particle mass. In the same vein, we can advocate sister universes for all the model parameters. Presenting an explicit example, in the benchmark universes displayed in Fig. 7, we display one conceivable sister universe of \mathcal{F} -U2 out of an innumerable distribution of sisters, that being the $M_{1/2}$ sister universe \mathcal{F} -U3. Inasmuch as universe \mathcal{F} -U3 will brandish different M_V , m_t , $\tan\beta$, and M_Z , it will feature a common gaugino mass with universe \mathcal{F} -U2. The effect the sister attributes will imprint upon the tangible architecture of each universe is unknown, though one could lucidly speculate that sister parameters could translate into some analogous physical properties.

VI. CONCLUSIONS

Modern Science has observed radical advancements in our conceptions of the cosmos as we peer deeper into the “heavens”, both immeasurably far above and sub-microscopically small below. One of the most captivating conjectural notions in recent memory is the suggestion of a Multiverse, capable of resolving persistent dilemmas regarding the apparently finely-tuned physical properties of our universe. Nevertheless, historically the concept of a Multiverse has represented a generic solution with no model building aspects attached to it, since there existed no effective model capable of building the universes pervading a legitimate testable framework. We have introduced here a analytical attempt at “universe building”, constructing the Multiverse from a specific fundamental high-energy theory capable of describing our observable low-energy physics.

The framework we apply for our local dominion of universes is the model dubbed \mathcal{F} - $SU(5)$, which as we have shown here and in our numerous previous explorations, has proven an extraordinary consistency amongst param-

eters dynamically determined (the top-down approach) and parameters evaluated through application of the latest experimental constraints (the bottom-up approach). Forged upon the foundations of the flipped $SU(5)$ GUT, extra TeV-Scale vector-like multiplets derived out of F-Theory, and the dynamics of No-Scale supergravity, \mathcal{F} - $SU(5)$ has not only persevered in the face of rapidly progressing constraints imposed by the LHC (while most alternative supersymmetric models such as mSUGRA and the CMSSM have been decimated), but \mathcal{F} - $SU(5)$ also moreover cleanly explains recent low-statistics excesses in multijet observations at the LHC. Hence, the \mathcal{F} - $SU(5)$ is demonstrating itself to be a credible contender for the supersymmetric GUT for our universe. We suggest that experimental substantiation of a No-Scale \mathcal{F} - $SU(5)$ composition for our universe will thus enhance the case for string, M-, and F-Theory as a master theory of the Multiverse, with a ubiquitous No-Scale structure. As such, we have here constructed a locally phenomenologically adjacent sector of the Multiverse from our \mathcal{F} - $SU(5)$ M(universe)-Theory.

By dynamically determining numerous points within the model space, we assembled a hypervolume of minimum minimorum, each point representing a distinctive EWSB vacuum capable of describing a unique universe. A viable candidate for our universe was presented that thus far nicely matches our observable phenomenology, and we offered up potential sister universes we may have inherited. Curiously, the fine threads of our journey into the Multiverse revealed two profound fundamental correlations, that of $M_{1/2}=\mu$ and $\tan\beta(\text{WMAP})=\tan\beta(\text{MM})$. Any direct correspondence between the gaugino mass and the μ parameter could have significant ramifications toward a solution to the μ problem in the supersymmetric Standard Model, hence we continue to closely study this most interesting correlation. The surprising connection between disparate approaches to the derivations of $\tan\beta$ at low-energy is of equal significance, insinuating an inseparable linkage between physically measured observables and the theoretical dynamics of \mathcal{F} - $SU(5)$.

We have come historically to fully expect new revelations that will continue to challenge that which our imaginations can perceive. Though the notion of a Multiverse initially boggles the mind, as with many striking new developments in science and technology, such innovative conceptions may eventually gravitate from bizarre to canonical. We anticipate that as the Multiverse framework continues to be rationally probed by sound principles of physics, the idea that our universe is but one among an innumerable host will come to seem not so outlandish after all.

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\mathcal{F} - Landscape Sister Universes

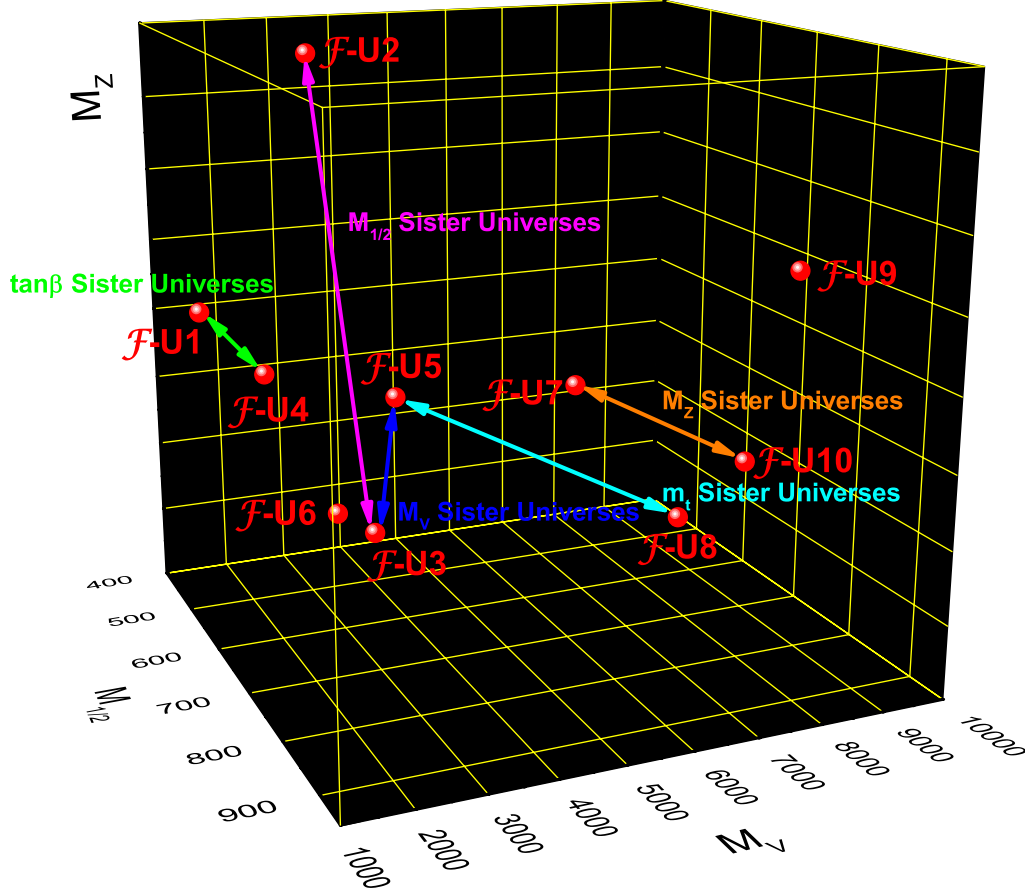


FIG. 7: Three-dimensional diagram in $(M_{1/2}, M_V, M_Z)$ space of the ten benchmark universes of Table I, highlighting the Sister Universes of these ten benchmarks. The Sister Universes are those that have an identical parameter to another universe. Each of the universes shown here are enclosed within the hypervolume of Fig. 4, though not shown here for clarity.

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